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A Comparison of LED Lighting Performance For Supermarket Vertical Refrigerated Display Cases

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ABSTRACT

The advantages of LED over fluorescent lighting for supermarket vertical refrigerated display case applications are well documented. Two types of LED luminaires are currently offered for this application, high-power LED and low-power LED. Low-power LED luminaires are a superior solution from the standpoint of both better optical performance and expected useful life. Higher levels of light distribution and uniformity can be achieved without the need for sophisticated optics or thermal management schemes and because drive current and resulting semiconductor junction temperatures are lower, longer luminaire life can be realized.

1. INTRODUCTION

For more than 50 years, fluorescent lights have been used for illumination in supermarket refrigerated display cases. Particularly in the Reach-In vertical light application, fluorescent lights are used to provide uniform light distribution from top to bottom in the case. Fluorescent lighting has, however, always suffered from a specific shortcoming: because the distance between the light source and the illuminated surface in vertical refrigerated display cases can vary from 2.54 cm - 15.2 cm (1 inch to 6 inches), this type of lighting is limited in the capability to provide uniformity from the mullion to the center of the door.

Uniform light distribution is critical to the perceived quality of a lighting system. In addition, there are other parameters, such as energy usage and utilization of the light output, which fluorescent lighting is only partially capable of fulfilling satisfactorily. The advantages of LED lighting over fluorescent in supermarket vertical refrigerated display case applications have been discussed by Anderson (2008).

A misconception exists in some parts of the supermarket display lighting industry that high-power LED's (>300 mA current intensity LED's) are the only viable choice for replacing florescent lights. But we have concluded through our investigation and research efforts that low-power LED's (20 – 70 mA current intensity LED's) are a superior solution. This paper will discuss performance in terms of optical design and reliability considerations of high-power LED's versus low-power LED's for supermarket refrigeration vertical lighting applications.

2. OPTICAL DESIGN CONSTRAINTS

The optical performance of a luminaire is determined by efficiency and light distribution, both of which are dependent on light source orientation as well as the lens and extrusion design ("Position Paper on Solid State Lighting in Efficiency Programs", 2010). The optical design constraints that influence lighting system performance in supermarket vertical refrigerated display case applications include:

- Distance between light source and surface to be illuminated - because of their high luminous intensity and large lumen per unit area output, high-power LED's are well suited for applications with large distances between the light source and the illuminated surface such as street lighting, general lighting applications, automotive high beam lighting, flash lights, etc., but not as well suited for the supermarket refrigeration vertical lighting application for which the distance between the light source and the illuminated surface is small.

- Uniformity of the light across the products in the display case - the luminous intensity of low-power LED's spreads in a linear direction, similar to fluorescent lighting, without the need for a sophisticated optical design, thereby avoiding associated optical losses. High-power LED's require a sophisticated optical design to control light dispersion and obtain uniform light distribution; this greater optical manipulation will result in losses.

- Heat sink design and thermal management - due to the lower current intensity for a given linear length, low-power LED's require less heat sinking and thermal management than high-power LED's, resulting in a more streamlined design and greater ease of manufacture.

- Uniformity across the display case from top to bottom and left to right – in a typical Reach-In display case vertical lighting application, approximately twenty low-power LED's are used per linear foot as compared to two high-power LED's, which results in greater light uniformity. Figures 1 through 4 below illustrate the difference in design and resulting light uniformity between a typical low-power LED luminaire and a typical high-power LED luminaire.

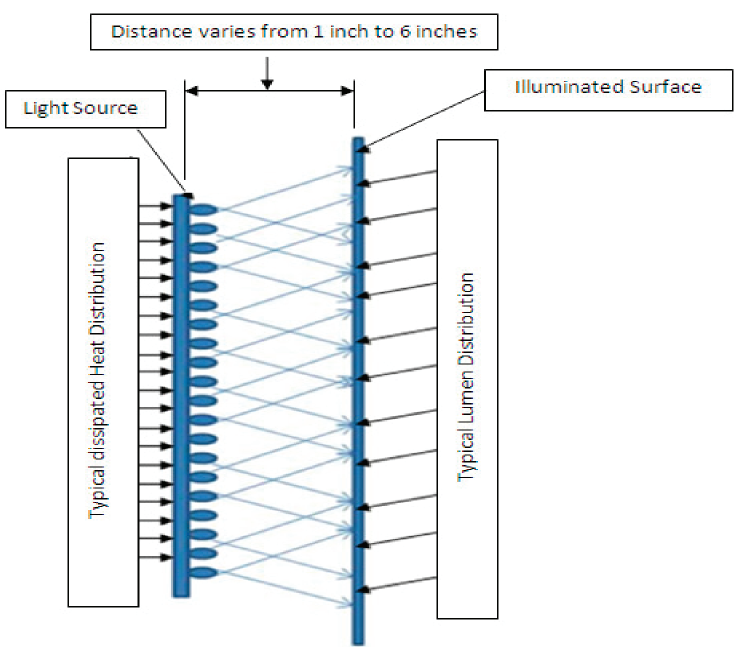

Figure 1: Typical low-power LED luminaire with LED average current intensity of 20 mA
(Note that secondary optics are not essential and heat sinking requirements are reduced)

Figure 2: Typical low-power LED luminaire

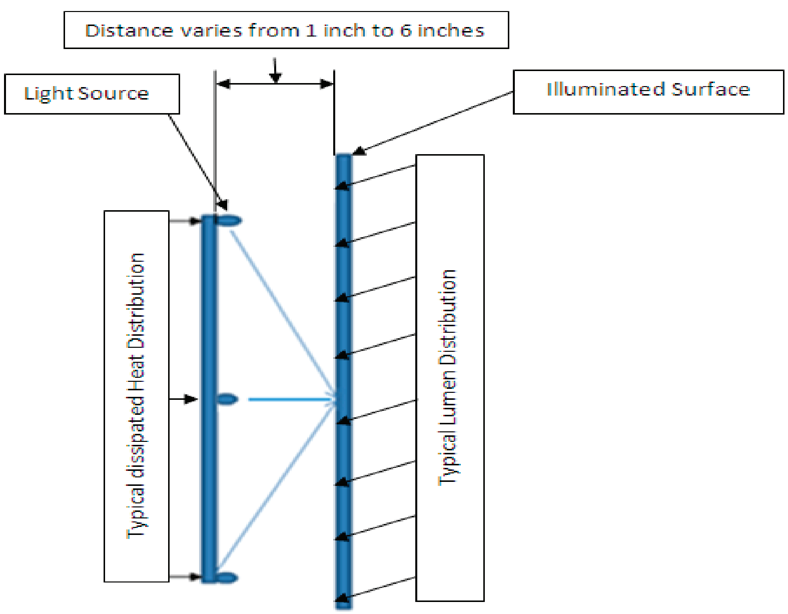

Figure 3: Typical high-power LED luminaire with LED average current intensity of 350 mA
(Note that secondary optics and robust heat sinking are required)

Figure 4: Typical high-power LED luminaire

3. RELIABILITY CONSIDERATIONS

Reliability of both low and high-power LED luminaries is dependent on several factors. Each factor will be discussed below, ending with a comparison of low and high-power LED luminaires in the refrigerated display case application.

3.1 LED Package-Level Reliability

The reliability or useful life at the LED package level is determined by two general failure modes: 1) lumen degradation, in which the luminous output of the LED deteriorates prematurely, and 2) catastrophic failure, in which the LED package ceases to emit light entirely. Each of these failure modes is due to separate mechanisms as will be discussed below.

Assuming well-controlled manufacturing processes, lumen degradation at the LED package level will be the far more common reason for which a luminaire fails to meet its useful life target. The main factor contributing to degradation in luminous output at the LED package level is generally considered to be excessive heat at the semiconductor p-n junction leading to 1) nonradiative recombination, 2) phosphor degradation, and/or 3) material degradation of the package encapsulant. In addition, LED package-level luminous output may also be affected by increased contact resistance due to die-attach degradation (Narendran and Gu, 2005, Meneghesso, *et al.*, 2003, Nogueira, *et al.,* 2009).

LED junction temperature is affected by three parameters (Anderson, 2008, Whitaker, 2009):

- Power dissipated by the LED (drive current)
- LED package thermal management
- Ambient temperature of the LED’s immediate surroundings

Of these, both the nominal drive current and the thermal management scheme are elements of luminaire design and both have a significant impact on junction temperature. For example, the calculated junction temperature for a typical low-power LED package, driven at less than 50 mA and dissipating less than 0.15 watts, is approximately 43°C, compared to 93°C for a typical high-power LED, driven at approximately 350 mA with power dissipation of approximately 1 watt.

In lieu of junction temperature, many suppliers measure what is referred to as the "T-point" temperature, which is the temperature at the interface between the semiconductor device and its mounting pad, or at the connection of the LED to circuit board. Here again, LED package design has a direct and significant impact on the measured temperature, with a typical T-point temperature of less than 40°C for a low-power LED driven at approximately 40 mA, compared to 76°C for a typical high-power LED driven at approximately 350 mA. Figure 5 provides a graph of estimated life as a function of T-point temperature (Narendran and Gu, 2005).

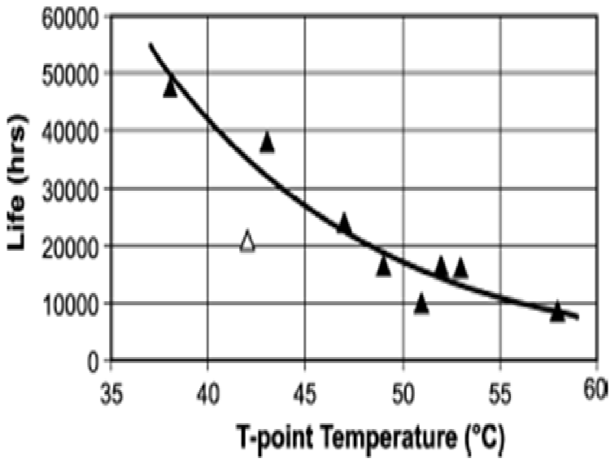

Figure 5: Estimated life as a function of T-point temperature

In addition to a robust thermal management scheme and low drive current, another method of minimizing lumen degradation is to limit the premature degradation of the converting phosphor in the LED package. One method to accomplish this is the incorporation of silicone/phosphor slurry with secondary epoxy encapsulation into the package design as shown in Figure 6 (Norris, *et al.,* 2006).

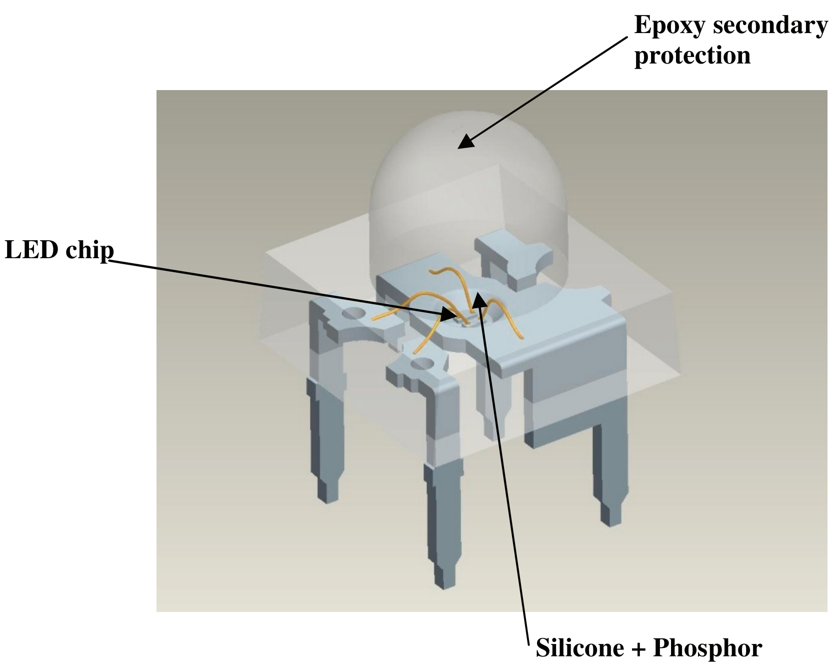

Figure 6: LED package with silicone/phosphor slurry
and secondary epoxy encapsulation

Catastrophic failure at the LED package level is generally due to wire-bond failures that are caused by either poor manufacturing processes or long-term environmental or usage effects such as corrosion or thermal fatigue. One recent study has concluded that wire-bond-related failures make up over 25% of life-limiting problems of electronic packages during manufacturing and reliability testing (Nogueira, *et al.,* 2009, van Driel, *et al*., 2009).

3.2 LED Luminaire Reliability

When assessing expected reliability of LED luminaires, it is important to note that in addition to factors which limit useful life at the LED package level, consideration must also be given to factors that limit useful life at the luminaire level ("Position Paper on Solid State Lighting in Efficiency Programs", 2010, Jacob, 2004, "LED Measurement Series: Luminaire Reliability", 2009). One of the most important factors in maximizing luminaire life is the inclusion of current regulation circuitry in the luminaire design. As discussed above, numerous studies have demonstrated a connection between elevated junction temperatures and lumen degradation at the LED package level, which would obviously result in a degradation of overall lumen output of the luminaire. A current regulation scheme minimizes the impact of any changes in drive voltage, assuring that the LED's in the luminaire are not inadvertently over-driven.

Related to the issue of over-current is the adequacy of the luminaire thermal management design, which must be effective in removing heat generated by the LED package, thereby keeping the LED junction temperature as low as possible to minimize lumen degradation ("Position Paper on Solid State Lighting in Efficiency Programs", 2010, Jacob, 2004). Catastrophic failures can also occur when inadequate heat sinking, combined with thermal cycling which occurs when luminaires are turned on and off, result in wire bond failures.

Other factors that may also contribute to curtailed useful life of an LED luminaire include degradation of the housing materials and the potential for accumulation of dust and/or dirt, either within or on the outside of the housing, that can block a portion of the output light (Jacob, 2004). It is, therefore, important to consider the application for which the luminaire is intended, to assess the degree to which these factors might contribute to a reduction in useful life, and to ensure that these factors are adequately addressed in luminaire design and application through appropriate material specifications, ingress protection ratings, and routine maintenance programs.

3.3 Factors Determining Luminaire Life in the Refrigerated Display Case Environment

The refrigerated display case environment differs significantly from the ambient environment for which LED luminaires are more typically purchased. Higher sustained humidity levels (typically 90% - 95% relative humidity), and the associated potential for corrosion, must be accounted for in assessing the suitability of a given luminaire design for this environment. Ingress protection and the ability of the luminaire circuitry, including any current regulation circuitry, to withstand high humidity levels should be considered. In addition, unlike ambient applications for which the luminaire is left on for most or all of the day, many refrigerated display case systems include a motion sensor coupled with a light dimmer to save energy by activating the case lighting to full power only when a customer is nearby. This power cycling is a potential source of thermal fatigue that should be accounted for in luminaire reliability testing.

The adequacy of a luminaire design for the refrigerated display case environment should be evaluated through a robust supplier testing program that includes an evaluation of lumen degradation at the luminaire level in the intended operating environment and an accelerated reliability life test focusing on both corrosion and thermal fatigue as primary failure modes.

One final consideration in assessing anticipated long-term performance of a given luminaire design is the type of LED's used. Because high-power LED luminaires use a much smaller number of LED's, even a single LED failure will result in a significant reduction in the total lumen output, whereas a low-power LED luminaire could sustain several such events before any significant decrease in lumen output would occur. Assuming the same high-reliability design and manufacturing techniques are applied, a low-power LED luminaire, using a silicon/epoxy encapsulation scheme and on-board current regulation should provide higher levels of long-term performance.

4. CONCLUSIONS

Investigation and research shows that low-power LED luminaires are a superior solution compared to high-power LED luminaires for the supermarket vertical refrigerated display case application from the standpoint of both better optical performance and expected useful life. Through the use of low-power LED's and their inherent characteristics, higher levels of light distribution and uniformity can be achieved without the need for sophisticated optics or thermal management schemes. Drive current and resulting semiconductor junction temperatures are lower, translating into longer luminaire life. Assuming well-controlled manufacturing processes, low-power LED luminaires designs that include a method of minimizing of epoxy degradation and a method of drive current regulation should provide higher levels of long-term performance.

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